Seismic Imaging as a Means to Investigate Abandoned Underground Mines

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ABSTRACT

Abandoned mines underlying transportation infrastructure have caused damage to roads, bridges, and building structures. These underground features can manifest slowly as sinkholes or other subsidence events or rapidly in catastrophic failures. Property damage and potential loss of life require appropriate actions to correct these situations. Understanding the condition of abandoned underground mine workings and their extent enables engineers to make decisions regarding remediation strategies. NSA Geotechnical Services has had great success in determining the extent of subsurface ground features using seismic imaging and analysis.

A geophysical investigation was conducted to investigate subsidence along a highway in southeastern Kansas. A portion of the first 6,000 feet of US Highway 69 after it crosses from Oklahoma into Kansas is known to overlie abandoned, underground lead and zinc mines. These mines were active in the first half of the 20th century. It was not known if available mine maps were accurate. Since the 1940's, there have been several surface subsidence incidents near the highway believed to be related to the abandoned mine openings. NSA applied its **RockVision3D™** seismic tomographic imaging system to image two vertical profiles of the ground under US Highway 69. These profiles helped the Kansas Department of Transportation assess the condition of these abandoned mine workings and to determine if some strategy was required to mitigate any possible risks.

INTRODUCTION

Geotechnical engineers have struggled for years with the difficult task of characterizing geologic and past mining conditions that affect the design, stability, and safety of both civil and mining constructions/operations. Commonly, underground developments (mines, tunnels, foundations, etc.) are based on surface or underground investigative drilling programs that may not determine the true character or three-dimensional continuity of the materials/strata present, and may also not detect the presence of localized structural discontinuities (faults, shear zones, etc.) or prior excavations (old mine works). Geophysical techniques such as seismic reflection, seismic refraction, and ground penetrating radar have been used with some success to expand the knowledge of subsurface conditions prior to excavation; however, these techniques often interfere with the construction process and are time-intensive in terms of data collection and interpretation.

To improve the quality, continuity, and timeliness of geotechnical data for site characterization, NSA has developed a three-dimensional tomographic imaging system known as RockVision3D™. This system is based on the principle that acoustic waves travel through different materials at different speeds and with different attenuation rates. By recording the waveforms from known acoustic sources, three-dimensional maps can be constructed that infer the relative competence of the materials through which the waves travel. Although tomographic techniques are not new, advancements in the technology make tomography a practical tool for geotechnical site characterization. With the expanded subsurface information that volumetric tomography provides, the risks and expenses associated with underground developments in the vicinity of anomalous geologic features and/or old works (prior excavations) are greatly reduced.

NSA has had great success in determining the extent of voids, unconsolidated soils, and other ground features using seismic imaging and analysis provided by RockVision3D™. This paper presents case studies from some representative surveys conducted by NSA.

BACKGROUND: SEISMIC TOMOGRAPHY

Seismic tomography is based on the principle that acoustic waves have different propagation velocities through different types of ground. That is, seismic waves travel faster in strong, competent material and slower in weaker materials (e.g., voids, broken or weathered rock, soil) (Nur (1); Shea-Albin, et al. (2); Yu (3)). Velocity tomographic images represent the ground velocity as measured between seismic sources and receivers. The accuracy and resolution of a tomographic image is a function of the source and receiver geometry.

To determine the seismic velocities of a survey area, the time required for seismic energy to travel from known source and receiver locations is measured. The velocity is then computed by dividing the distance traveled from source to receiver by this travel time. In ground with a homogenous velocity distribution, this distance is simply a straight-line distance, or straight ray path, from the source to the receiver. However, in ground with velocity variations, this distance may significantly increase due to deviation of the ray path toward higher velocity ground between the source and receiver. With appropriate source and receiver geometry, it is possible to iteratively construct an accurate velocity model of the ground surveyed. Distortions in the velocity model may appear in varying degrees as a consequence of the ground characteristics and the source and receiver geometry. Figure 1 demonstrates this distortion for a simplified two-dimensional, source and receiver geometry.

Numerous factors may cause variations in velocity. Different ground types usually have different material/seismic properties, but variations within the same ground type are also commonly encountered. Variations in stress, fracture extent, water saturation, soil compaction,

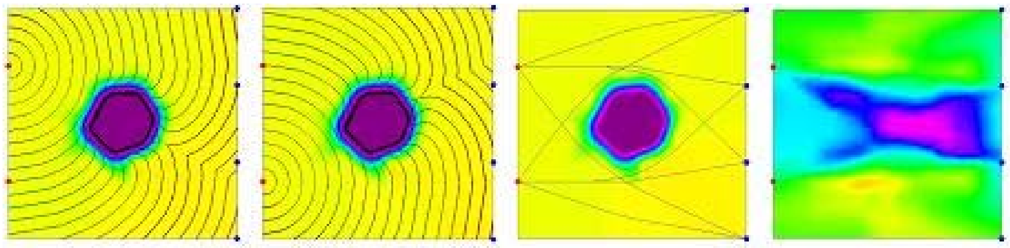

Figure1. Example of tomographic reconstruction.

etc., all may have a significant effect on velocity. In areas where geological features such as fracture zones, faults, subsidence zones, or cavities exist, the seismic waves may travel at a lower velocity, or may travel a longer distance around the anomaly, often resulting in higher attenuation. The same type of behavior may be noted in rocks of varying lithology as harder, more competent materials propagate seismic waves at higher velocity and lower attenuation than softer, less competent or less consolidated rocks.

ABOUT ROCKVISION3D

RockVision3D™ is designed to generate a seismic velocity model of the surveyed ground through multiple iterative reconstruction of the calculated seismic travel times (ray paths) determined from the field measurements of seismic ground velocity. The ray path and velocity models are constructed to estimate travel time and the curved path for each ray. Ray paths are calculated by propagating a finite-difference wave front across the surveyed groundmass from known source locations. For low-velocity contrasts, straight rays are often assumed. In higher velocity contrasts, rays will bend, resulting in longer ray paths. Differences between estimated and measured travel times are used to iteratively update the tomograms in regions along the ray path. Curved ray paths are adjusted to account for changes in the velocity mesh. Iterations are repeated until the velocity mesh converges to a solution. For this project, the velocity mesh represents a series of 2D sections (tomograms). These tomograms are color coded, representing various velocity ranges; purples/blues indicate low velocities (weaker materials), and yellows/reds indicate high velocities (higher rock competence).

BACKGROUND

A portion of the first 6,000 feet of US Highway 69 after it crosses from Oklahoma into Kansas is known to overlie abandoned, underground lead and zinc mines. These mines were active in the first half of the 20th century. It was not known if the available mine maps were accurate. Since the 1940's, there have been several surface subsidence incidents near the highway believed to be related to the abandoned mine openings. To assist in their effort to reduce the risk of catastrophic subsidence to US Highway 69, The Benham Companies, Inc. contracted NSA Geotechnical Services, Inc., to conduct a cross-borehole seismic tomography survey using its RockVision3D™ seismic tomographic imaging system.

Specifically, the objective was to produce two-dimensional tomographic images of the ground velocities within the specified area to (1) identify unmapped mine openings, and (2) indicate the existence and severity of any migrating caving zones above the old mine openings that might impact the engineering design, planning, and cost estimation of their various subsidence mitigation options.

SURVEY PROCEDURE

Between July 30 and August 2, 2002, an array of source and receivers was utilized in 17 drill holes along US Highway 69. Two hydrophone strings were used; a 12-phone hydrophone string with the phones on 2-m centers, and an 18-phone string on 1-m centers. On the latter string, only every other phone was activated to provide the 2-m receiver coverage required for this survey. The two hydrophone strings were moved within and between holes as needed to provide optimum seismic ray path coverage.

A downhole air gun was used as a seismic source and was discharged at 2-m intervals in the source holes. As each source signal was propagated, the time of the shot was recorded using a seismic trigger located very near (~ 1 ft) the source. For each source location, the trigger signal and signals from the hydrophone receivers were recorded with two Geometrics seismographs.

DATA ANALYSIS

Some ground information for the Hwy. 69 project within the survey area was known from the borehole data. This included ground type and quality along the borehole length and where the boreholes encountered voids or mine openings (see Figure 2). This information is shown next to each of the boreholes used for each tomographic figure, but was not used as input data into NSA's RockVision3D™ software prior to generating the tomographic images. The tomographic images included in this report were generated using only the raw seismic data as input.

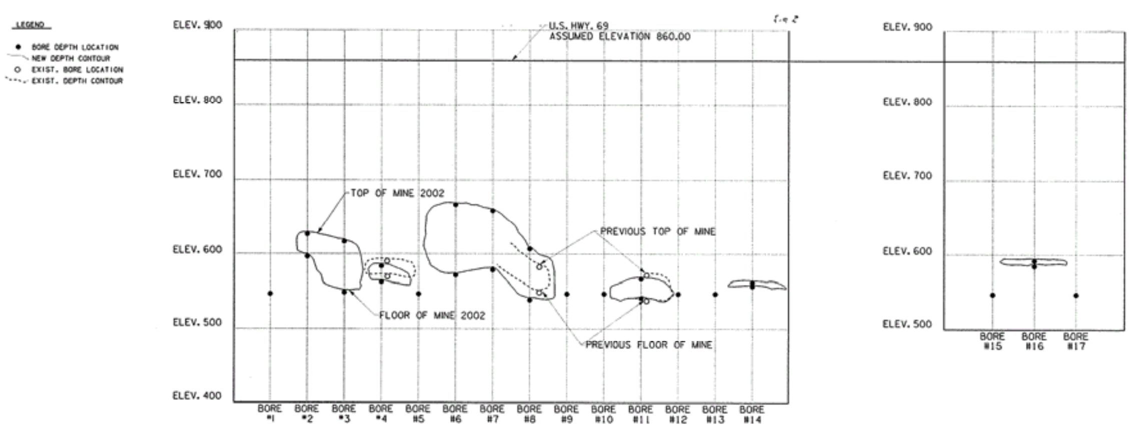

Figure 2. Vertical profile of voids encountered.

DATA INTERPRETATION

The majority of the data collected were of good quality. It is estimated that over 95% (approximately 29,000 ray paths) of the data collected were used to generate the images, and the ray path coverage was more than adequate to generate accurate images within the survey area.

Each of the survey image panels shows a low-velocity zone (blues and purples) near the surface, which indicates and correlates to the soils, weathered shale, and shale above the limestone. Below this near-surface low-velocity zone, a high-velocity zone indicating more competent ground and correlating with the limestone is represented by the color red. Low-velocity zones within the limestone and near the bottom of the images indicate mining voids, naturally occurring voids, or brecciated zones. Several naturally occurring voids were indicated in the boreholes. Also, some of the drill logs indicated the presence of pyrite crystals, which require voids for formation.

A tomographic, seismic velocity ground image was produced for each adjacent pair of boreholes resulting in the 15 two-dimensional images, shown as a composite image in Figure 3. Limestone of varying degrees of competence exists throughout the panels, usually of significant thickness (20 m to 50 m). The images were evaluated for indications of (1) any mine voids in addition to those indicated in the available mine maps, (2) mine roof failures migrating toward the surface, and (3) the thickness of competent rock between the top of the mine voids and the surface to evaluate the probability of near-term failures to the surface. Regardless of their origin (natural or mining-related), the potential of any voids detected to impact the final design should be evaluated.

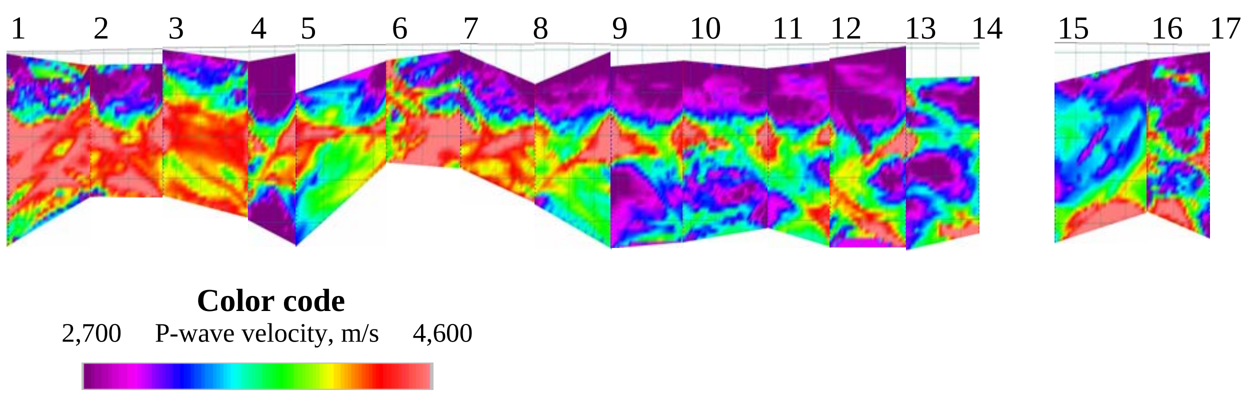

Figure 3. Composite image of panels resulting from seismic surveys.

Below is a summary of the results for the fifteen panels. For the panels of special note, where voids were detected, enlarged figures are provided:

Panel 1-2 indicates the presence of approximately 40 m of competent limestone between the mine void encountered in Boring #2 and the shale zone. Some lower velocity zones adjacent to and near the bottom of Boring #1 are evident, possibly associated with localized voids (indications of pyrite were noted in the driller's logs in this zone).

Panel 2-3 indicates the presence of approximately 30 m of competent limestone above the mine void, with no indication of roof failure migration toward the surface. There is a localized void/zone of weakness at the bottom of Boring #2.

Panel 3-4 indicates the presence of more than 40 m of competent limestone above the mine opening. Some lower-velocity zones exist, but do not appear to be associated with roof failure migration or significant voids.

Panel 4-5 (Figure 4) indicates the presence of approximately 25 m of competent limestone beneath the shale, but a large void, likely caused by mine roof failure migrating toward the surface is present.

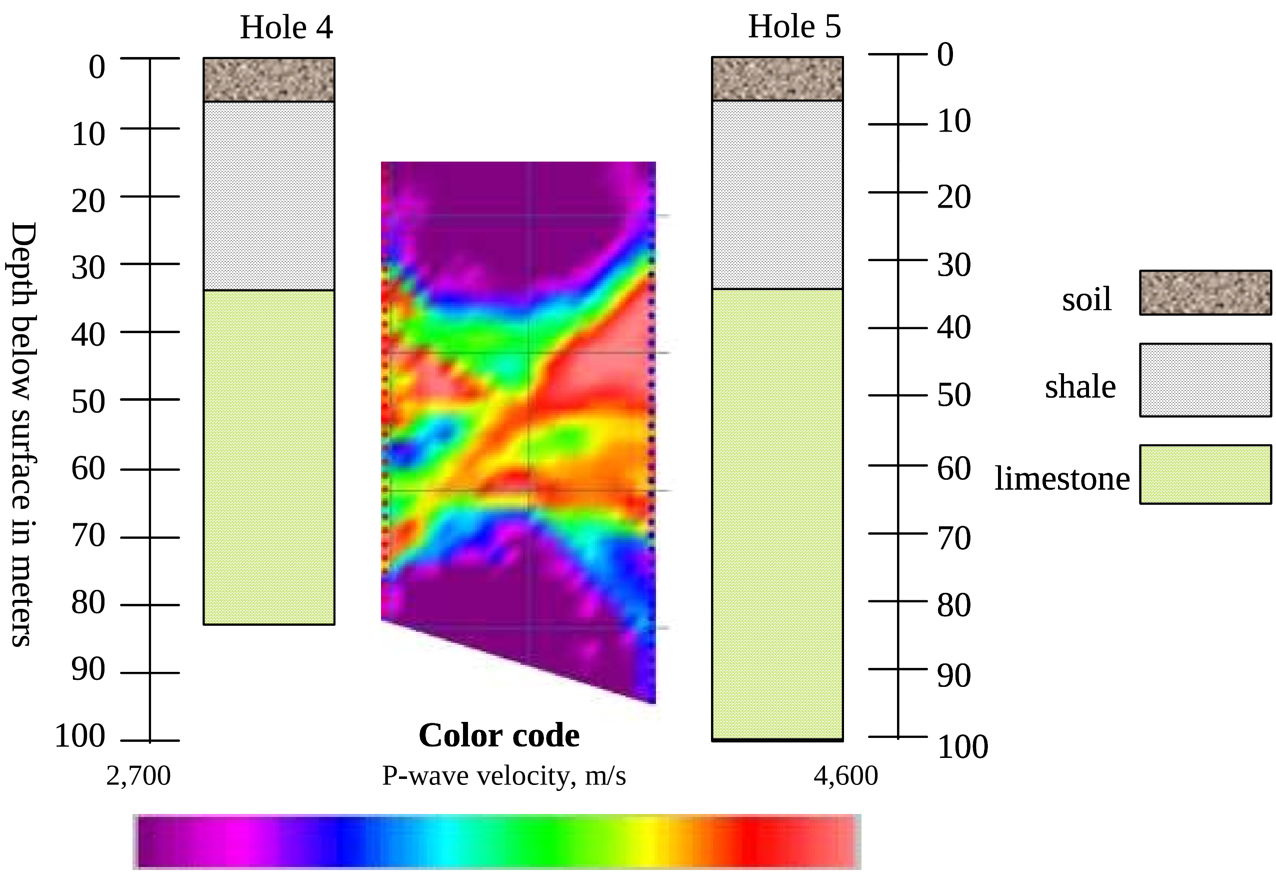

Figure 4. Panel 4-5 with borehole geologic profiles.

Panel 5-6 (Figure 5) shows that only a thin (approximately 5-m) layer of competent limestone exists between the mine roof and the shale. The remaining limestone appears to be less competent. There is no indication that roof failure has migrated up through this weaker limestone layer, but the potential for roof failure migration is likely higher in this area because of the reduced limestone competence.

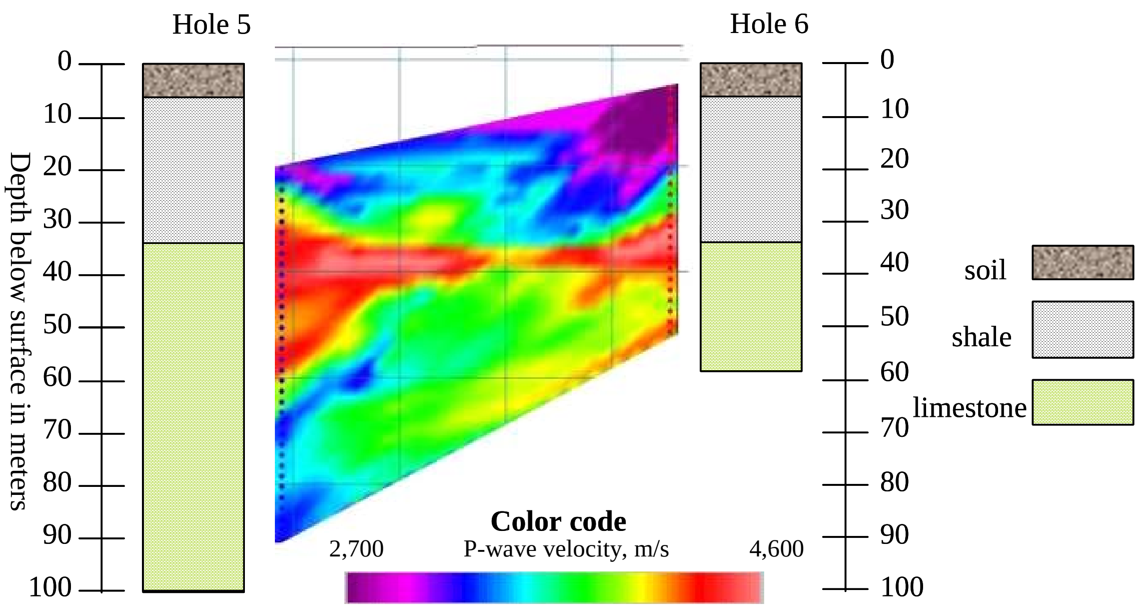

Figure 5. Panel 5-6 with borehole geologic profiles.

Panel 6-7 indicates the presence of approximately 40 m of competent limestone above the mine opening, with an indication of weaker material (possibly voids or brecciation) near Boring #6. It does not appear that this zone of weakness is associated with roof failure.

Panel 7-8 indicates lower velocities within the approximately 20-m-thick limestone are probably associated with local variation in limestone competence. No indications of roof failure are evident.

In Panel 8-9, competent limestone is evident (approximately 30 m near Boring #8 and approximately 70 m near Boring #9), although velocities in the limestone are markedly lower than in previous panels. This is probably due to numerous small voids or brecciation within the limestone, rather than to roof failure migration.

Panel 9-10 (Figure 6) indicates a large void between Boring #9 and Boring #10, closer to Boring #9. The drill log indicated water in this area, but no indication of a mine void. This could possibly be a breccia zone. About 20 m of competent limestone separates the void and the shale.

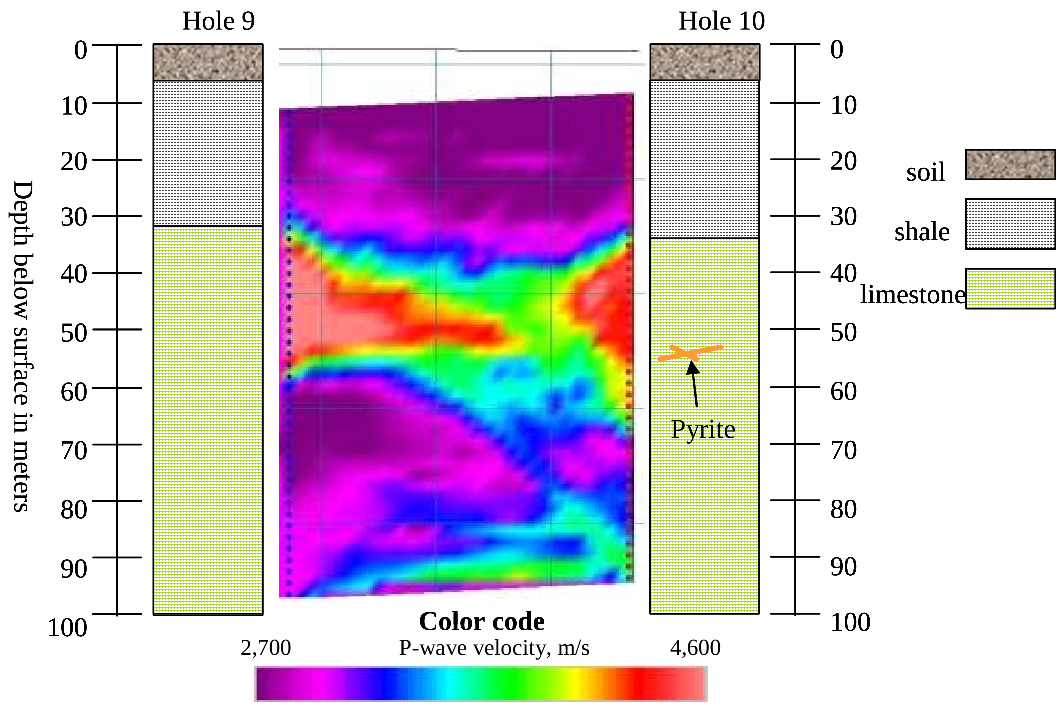

Figure 6. Panel 9-10 with borehole geologic profiles.

Panel 10-11 (Figure 7) indicates the presence of approximately 20 m of competent limestone beneath the shale. Beneath this competent zone, about 30 m of less competent limestone is indicated. This less-competent zone appears to be brecciated or otherwise weakened, although the possibility of migrating roof failure cannot be ruled out.

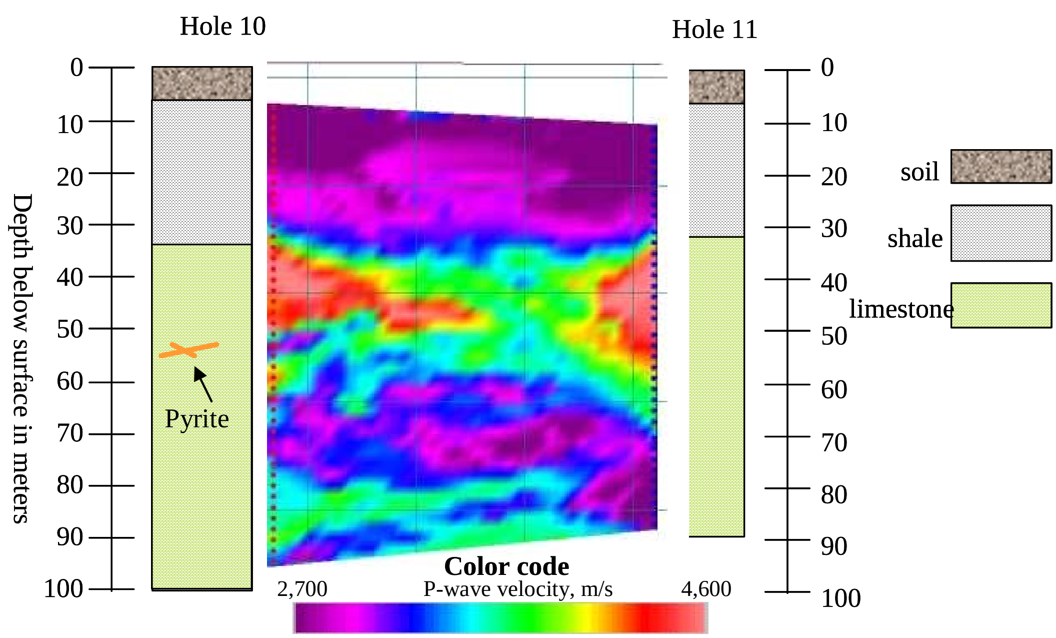

Figure 7. Panel 10-11 with borehole geologic profiles.

Panel 11-12 indicates the presence of approximately 50 m of competent limestone above the mine roof, with voids/weak zones at depths of 70 to 80 m near Boring #11, and 55 to 65 m near Boring #12. These zones appear to be unrelated to roof failure migration.

Panel 12-13 indicates the presence of approximately 40 m of competent limestone beneath the shale, with a void/weakened zone at a depth of approximately 60 m near Boring #13. No roof failure migration is evident.

Panel 13-14 (Figure 8), shows that apparent voids exist between Borings #13 and #14, closer to Boring #13. Because of their location, it is surmised that these voids are naturally occurring rather than mining-related.

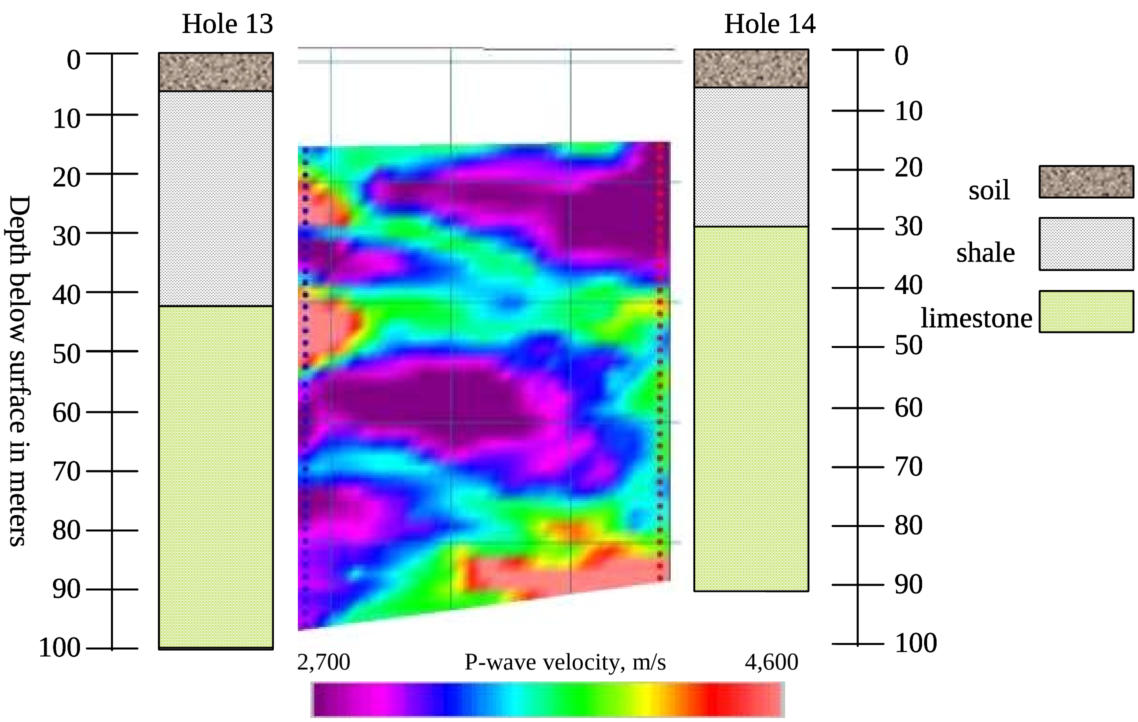

Figure 8. Panel 13-14 with borehole geologic profiles.

In Panel 15-16, competent limestone (approximately 20 m) is indicated above the mine opening, overlain by less competent limestone. No roof failure is evident.

Panel 16-17 (Figure 9) indicates the presence of approximately 10 m of competent limestone above the mine roof; the remainder of limestone (approximately 40 m) shows areas of voids/weakness/ brecciation.

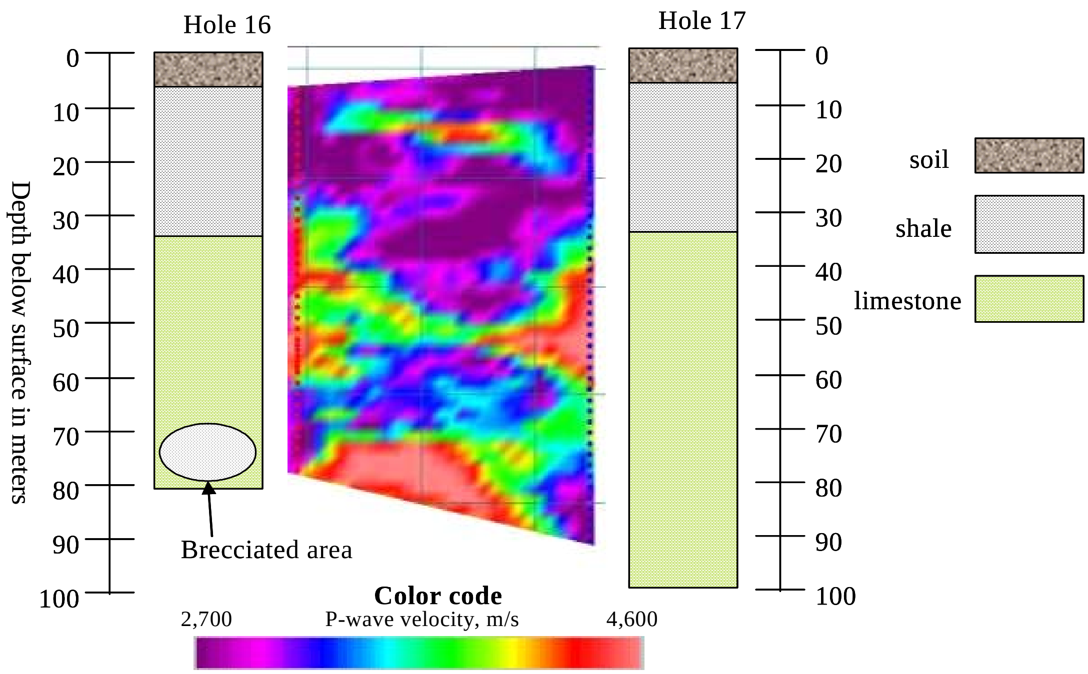

Figure 9. Panel 16-17 with borehole geologic profiles.

CONCLUSIONS

Because of their potential impact on roads, bridges, tunnels, and other transportation infrastructure, it is important to be able to determine the existence, location, and extent of mine workings. Since mine maps and other documentation offer less than exact documentation for mining activities, it becomes necessary to consider methods for geotechnical investigation. Seismic imaging using RockVision3D™ can provide an accurate description of the location and extent of mine workings. In this case, the results of the survey correlated well with the in-place mine workings verifying the accuracy of the available mine maps. Also, this technology can offer some current information regarding the conditions of these mine workings with respect to considerations such as roof failures, pillar failures, and fracturing. With this information, engineers are better able to determine the impacts of mine workings on transportation infrastructure, surface features, and subsurface excavations.

REFERENCES

1) Nur, A. Seismic Rock Properties for Reservoir Descriptions and Monitoring. In *Seismic Tomography with Applications in Global Seismology and Exploration Geophysics*, G. Nolet, ed., D. Reidel Publishing Co., Dordrecht, The Netherlands, 1987, pp. 203-237.
2) Shea-Albin, V. R., D. R. Hanson, and R. E. Gerlick. *Elastic Wave Velocity and Attenuation as Used to Define Phases of Loading and Failure in Coal.* USBM Report of Investigation 9355, U.S. Bureau of Mines, Department of the Interior, 1991, 43 pp.
3) Yu, G. *Elastic Properties of Coals*. Ph.D. Thesis, MacQuarie Univ., Sydney, Australia, 1991, 133 pp.